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Hybrid Propulsion Demonstration Program 250K Hybrid Motor

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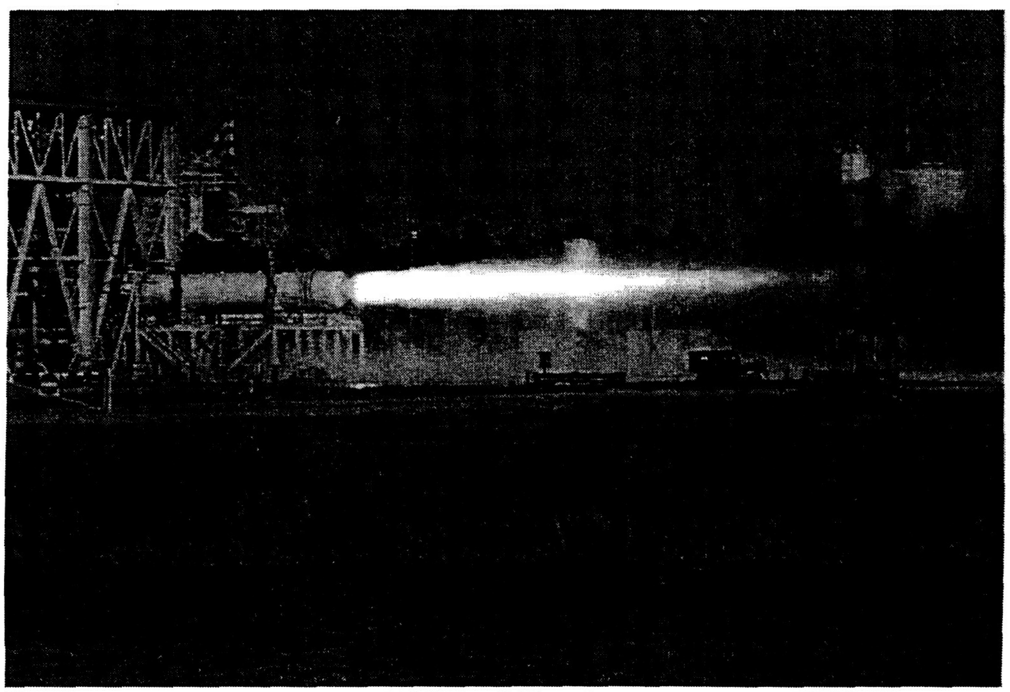
Abstract

The Hybrid Propulsion Demonstration Program (HPDP) program was formed to mature hybrid propulsion technology to a readiness level sufficient to enable commercialization for various space launch applications. The goal of the HPDP was to develop and test a 250,000 pound vacuum thrust hybrid booster in order to demonstrate hybrid propulsion technology and enable manufacturing of large hybrid boosters for current and future space launch vehicles. The HPDP has successfully conducted four tests of the 250,000 pound thrust hybrid rocket motor at NASA's Stennis Space Center. This paper documents the test series.



Motor 2 Test 3

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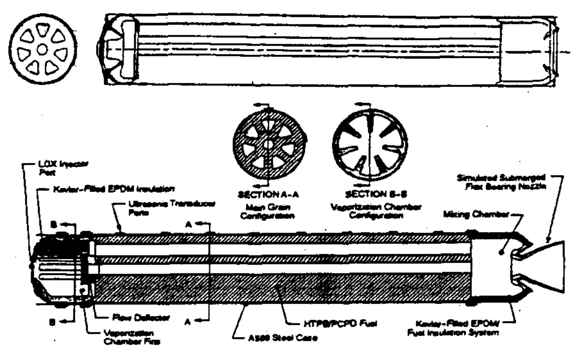

Figure 1 - 250K HPDP Layout

Nomenclature

C*: Characteristic exhaust velocity
GOX: Gaseous oxygen
HPDP: Hybrid Propulsion Demonstration Program
HTPB: Hydroxyl Terminated Polybutadiene
ISP: Specific impulse
LOX: Liquid oxygen
MSFC: Marshall Space Flight Center
O/F: Oxidizer to fuel ratio
PSD Power Spectral Density
SSC: Stennis Space Center
TEA/TEB: Triethylaluminum/Triethylborane
TEAL: Triethylaluminum
TNT: Trinitrotoluene

Introduction

Hybrids, considered part solid and part liquid propulsion system, have been caught in the middle of development goals of the various NASA and military programs. Solid rocket motor technology has matured due to the design simplicity, on-demand operational characteristics and low cost. The reliability of solids, given minimal maintenance requirements, made them the ideal system for military applications. On the other hand, liquid rocket engine technology has matured due to their higher specific impulse (ISP) over solids and variable control capability.

Hybrid Rockets have been used in only one flight-production application (Teledyne Ryan AQM-81A 'Firebolt Supersonic Aerial Target), suggesting that advantages have been over looked in some potential applications. Hybrid rockets inherently combine the safety features of a liquid propulsion system (throttle, shut-down, restart) while deriving the cost and operational benefits of a solid propulsion system. Specific details regarding these advantages include the following:

Handling – Virtually all hybrids fuels are considered inert (Class 1.4c propellant – zero TNT equivalent), that is they can be transported via normal shipping techniques with no additional safety requirements. This is a significant benefit when compared to traditional solids, where any processing is considered a hazardous operation and special handling considerations must be observed.

Casting – Classical hybrid motors can be cast in light industrial facilities using the techniques used in traditional solid propellant casting. Even though hybrids are insensitive to cracks and defects in the propellant, gross disturbances in the flow from air bubbles cast in the fuel (voids) can causes problems during hot-fire operations.

Simplicity – Hybrid rockets are more complex than solids due to the need for an oxidizer delivery system, with an associated oxidizer tank pressurization system and pump if necessary. Although hybrids are more complex than solids, they use only one fluid system, which make them less complex than bi-liquid systems (liquid rocket engines).

Throttling – Hybrids can be throttled by increasing the oxidizer flowrate via varying the opening of the oxidizer valve in a pressure fed system or speeding the pump in a pump fed system. Since the fuel regression rate is a function of the oxidizer flux, lowering the oxidizer flow rate lowers the fuel regression rate and resultant thrust level.

Restart – Hybrid motors can typically be ignited many times, until the fuel grain is consumed or the nozzle is past it's design limits.

Performance – The ISP of a Hydroxyl Terminated Polybutiene - LOX rocket is equivalent to a RP-1-LOX engine, and significantly higher than a solid rocket motor. For this program, additives were incorporated to increase resilience and durability verses straight HTPB fuel, but this lowered the performance slightly (see Figure 2). [16]

Cost – The handling and casting process costs should be significantly lower than that of a solid. Since there is only one oxidizer used, the system costs should be significantly less than that of a liquid system.

HPDP was formed to develop hybrid rocket technology to the point where US companies could use these advantages in a system and commercialize it for launch vehicle applications [1][2]. Participants in HPDP have included Allied Signal Aerospace, Boeing – Rocketdyne Division, , Environmental Aerospace

Corporation , Lockheed Martin, Thiokol, United Technologies Corporation – Chemical Systems Division and NASA (MSFC and SSC).

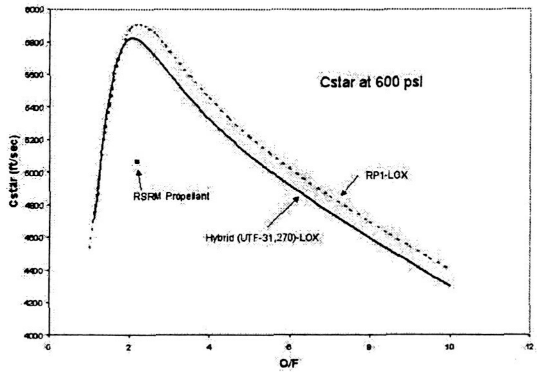

Figure 2 Theoretical Cstar Performance of UTF-31,270 with LOX

250K LBF Thrust Hybrid Test Motor

The 250 K hybrid motor was designed by the HPDP consortium to develop hybrid technology to the point where the propulsion industry would be able to commercialize the technology. Design requirements are shown in Table 1. Details of the injector, fuel grain, nozzle design are shown in references [1] and [2]. Those references did not discuss the two head end designs used in the program. A photo of a pretest aft end of the grain is shown in Figure 3.

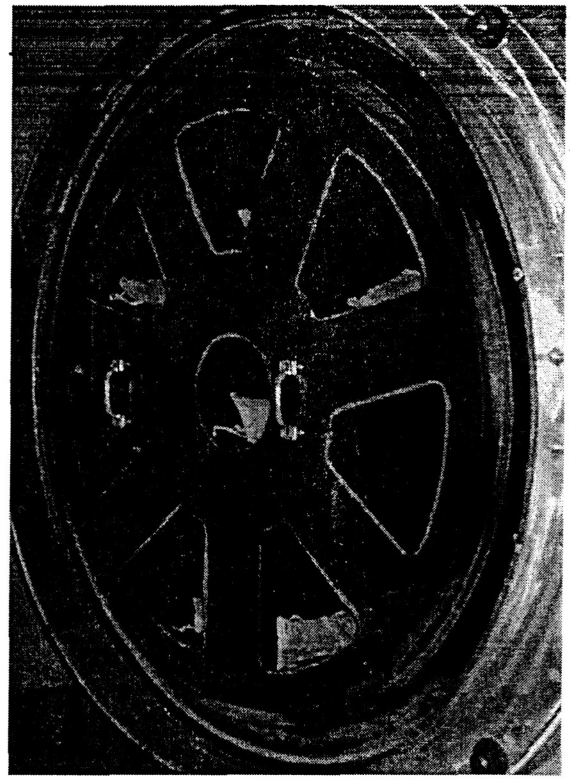

Figure 3 250K HPDP Motor Ports

Table 1 250K Design Parameters

Parameter	Value
Max. Vacuum Thrust	250,000 lbf
Ave. Vacuum Specific Impulse	280 sec
C* Efficiency	98%
Max. Operating Pressure	900 psia
Ave. Chamber pressure	750 psia
Burn Time	80 sec
LOX Flow Rate	600 lbm/sec
Oxidizer Flux Level	0.64 lbm/sec/in^2
Port Length	380 inch
Length to Diameter Ratio	35.3
Fuel	HTPB/LOX*

* HTPB and polycyclopentadiene (PCPD) with no metal additives

Head end designs

Combustion stability is an issue facing the development of large scale hybrid rockets[3][4][5]. The HPDP consortium came up with two ways to try to control the combustion instability: a passive technique, with no moving parts, employed in Motor 1 and an active approach, utilizing heat addition from the forward end, employed on Motor 2.

Motor 1 Design Basis and History

The Motor 1 head design was based upon previous solid fuel ramjet stability historical data, with the creation of 'a stable zone of hot, recirculating, combustion gases ahead of the of the establishment of the primary combustion zone.' Several of these concepts were designed and subscale tested with gaseous oxygen (GOX) in the 11-inch diameter motor, which was ignited with an oxygen hydrogen torch. 'All oxidizer dump plenum configurations that produced flow recirculation of combustion gas at the leading edge of the diffusion flame sheet resulted in stable operation. Configurations that did not produce such flow structures exhibited unstable combustion.' [6]
Testing with LOX in the 11-inch diameter hybrid motor produced similar stability results. 'The comparison showed that flow field features which reduced or eliminated acoustic oscillation in motors using gaseous-oxygen injection were also required to stabilize combustion in liquid-oxygen-injected motors.' This testing evaluated the effects of short and long fuel lined vaporization chambers with different flame holding concepts – fuel fin, flame holder and fuel inhibitor. The LOX was injected with either a solid cone or axial injector. The combination of the long fuel lined vaporization chamber with the fuel fin and the solid cone injector had the lowest average nonaccoustical oscillation amplitude percentage and also had the highest vaporization chamber heat output. It was determined by the authors that 'Fuel fins are effective in both short and long vaporization chambers in reducing the average instability level associated with liquid-oxygen injection. This is most likely because of the combustion port, spanwise, hot-gas recirculation zone behind the fuel fin and flame from combustion on the fin surface entering the combustion port. Incorporation of fuel fins appears to offer a viable means of scaling a combustion oscillation suppression method to larger liquid oxygen based motors.' [7] This work supported the concept that became the bases for the design of motor 1's head end.
Testing with the 24-inch diameter LOX motor was started in parallel with the 11-inch diameter GOX motor testing to support the ramjet combustion stability concepts.[8] Testing was done with domed shaped vaporization chambers with varying length fins and no fins. This published reference [8] had no conclusions listed on the effect of fins, however it did support previous American Rocket Company (AMROC) conclusions stating that the oxidizer feed system must be decoupled from the motor oscillations. This decoupling was implemented by moving the cavitating venturi, which regulates the liquid oxygen flow, from well upstream of the injector to right before the injector. A well designed cavitating venturi speeds the fluid to the point where the local fluid pressure is less than the vapor fluid and the fluid flashes, and then the flowrate is controlled by the vapor pressure, not the down stream pressure. This effectively eliminated the feed system coupling of the oscillations with the motor oscillations. [3] Subsequent HPDP testing of the 24 inch hybrid evaluated the effect of the center port on combustion efficiency. [9] [10] These tests were investigating the effect of the center port on the motor combustion, by blocking the center port with a fuel plug or making a tortuous path to the center port by use of a fuel flow port deflector. Blocking the center port lead to more stable motors compared to unblocked center port motors, but the center port open motors were within the +/-2.5 % stability band HPDP requirements. The +/-2.5 % stability band was an indicator of the stability, based on the pressure variations verses a 1 second moving average of the low speed chamber pressure. The final motor of that 24-inch diameter series incorporated a flat-topped fuel flow deflector, a fuel lined vaporization chamber with fins and a nozzle throat designed to provide a chamber pressure of 900 psi. This configuration of motor 'showed that altering conditions in the center port provided a more stable motor with high combustion efficiencies. Results from the incorporation of the fuel flow deflector also indicate that a more uniform regression along the length of the grain was obtained. These data resulted in the incorporation of the fuel deflector into the first 250 Klbf motor.' [9]

Motor 2 Design Basis and History

Motor 2's head end design was also influenced greatly by historical data, initially being based upon data from the American Rocket Company (AMROC). During the late 80's and early 90's, AMROC was the leader in hybrid technology. Some of their combustion stability experience is listed in a patent [11] and a paper on combustion stability [3]. Based on AMROC's testing, hybrid combustion instability was thought to be caused by several reasons, 'One of the causes of erratic performance is the flow of unvaporized liquid oxidizer, which disrupts the normally stable boundary layer combustion process. Ideally, during combustion a combustion zone is formed in the boundary layer at the interface of the vaporizing fuel flow and the vaporized oxidizer, within the momentum boundary layer and is the source of the heat flow to the surface of the solid fuel to maintain fuel vaporization. As unvaporized liquid oxidizer is distributed along the surface of the solid propellant (grain), the temperature of the forward reaction mixture is reduced, thus the efficient combustion area is developed toward the aft end of the rocket. As the pressure differences within the combustion area increase, the hot reaction products move forward into the area of low pressure and temperature, then aft again, producing a series of low frequency oscillations along the length of the grain. This results in erratic combustion and unstable thrust. Thus, it is essential for stable hybrid rocket engine performance that there is a consistent boundary layer over the entire solid propellant.'[11] Another large cause of combustion stability AMROC documented included feed system coupling with the hybrid combustion – this they addressed by a cavitating venturi just upstream of the LOX injector.[3] AMROCs correction of the boundary layer problem is to inject a phyrophoric liquid into the oxidizer stream to vaporize the oxidizer before entry into the combustion zone. 'The hypergolic fluid is injected in an amount sufficient to vaporize all of the liquid oxygen. The flow rate can be readily calculated from the temperature of the liquid oxidizer and the flow rate of the oxidizer. For example, a hybrid engine using liquid oxygen and a trialkyl aluminum pryogolic fluid, a flow rate of from about 0.1% by weight of the liquid oxidizer is sufficient to vaporize all the oxidizer. Flow rates higher than 5% by weight of the oxidizer are unnecessary and can lead to unstable burning. Usually the flow rate is from about 0.5 to 3.0% by weight of the oxidizer.' [11]

To support the claims in AMROC's patent, they included test data from a series of tests, using the configuration shown in Figure 4. 'Hybrid engines were constructed incorporating a polybutadiene solid grain and utilizing a casing containing a precombustion zone as shown in [Figure 4]. Liquid oxygen was utilized as the liquid oxidizer and triethyl aluminum (TEAL) as the hypergolic fluid. One engine (Example 1)[Figure 5 H8#1] was operated with TEAL only injected during initial start ups. Two other engines (Example 2 and 3) [Figure 5 H8#2 and H8#3] were operated with the TEAL injected continuously. Example 4[Figure 6] was a test burn lasting 70 seconds with TEAL continuously injected. Figure 5 shows three short test firings; Example 1[Figure 5 H8#1] shows the aft port pressure during a time when TEAL was not injected. Both Example 2 and Example 3 [Figure 5 H8#2 and H8#3] show the aft port pressure, under identical conditions, while TEAL was being injected. Example 1 shows the low frequency harmonics (oscillations) of hybrid rocket engines that have been reported in the literature while Example 2 and 3 show that said low frequency harmonics have been eliminated.'[11]

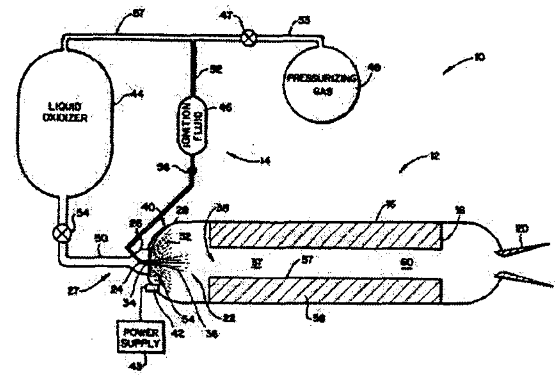

Figure 4 US Patent 5582001 Motor Layout

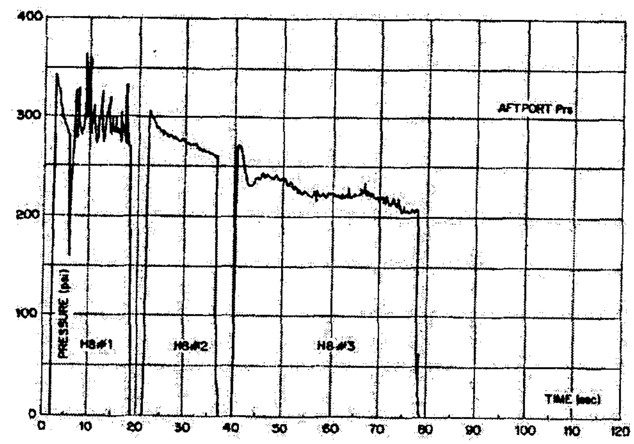

Figure 5 US Patent 5582001 Motor Plot 1

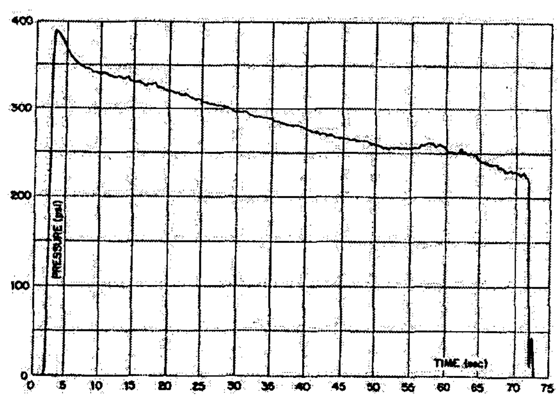

Figure 6 US Patent 5582001 Motor Plot 2

These AMROC conclusions were also somewhat supported by HPDP testing with LOX on the 11 inch motor. This series of motors were ignited by TEA/TEB, which is a mixture of pyrophoric liquids. 'The heat input from the TEA/TEB combustion is approximately 3,600 BTU/sec, substantially exceeding that available from steady state combustion of fuel in the vaporization chamber. Heat required to vaporize liquid oxygen is approximately 90 Btu/lbm, or approximately 400 Btu/sec at average motor liquid-oxygen flow rates. Thus the heat available from TEA/TEB combustion is well in excess of that necessary to vaporize the liquid oxygen. Examination of motor pressure data indicates that the effect of TEA/TEB combustion on stability appears to be significant in some cases and less so in others.' [7]

Motor 2's design (and Motor 1's also) came from the inherent safety conflict between a safe, solid inert hybrid fuel with a zero TNT equivalency requiring a pyrophoric liquid to start it and make it operate in a stable condition. The special care needed to handle the pyrophoric liquid had raised a question of the handling safety of the whole system. Also, members of the consortium had come to doubt if Motor 1 would be stable, so it was decided to test a concept where the ignition and the stabilizing heat would come from a hybrid instead of a pyrophoric liquid. Motor 1 retained the pyrophoric liquid for ignition purposes only.

Additional testing was done on the 11-inch and 24-inch diameter LOX motors to evaluate this concept. Reference [9] discusses the results of the 11-inch motor ignition system and the 24-inch motor vaporization system testing. Testing of both sized motors was done to see if small hybrids could start large hybrids and if the heat could keep it stable. Startup was smooth and combustion stability was increased compared to motors without this active heat source. The success of this testing led to the incorporation of the hybrid "heater motors" into the 24 inch Large Subscale Quad Port Test Series. "On test HP24-8020, the (GOX feed to the heater motor) system was terminated at T+11 seconds which caused the motor to go unstable.... The test confirmed the hypothesis, as shown in multiple 11- and 24- inch tests series, that the flame anchoring in the head end of a hybrid motor is essential for motor stability." [9]
The conclusion that heat addition was necessary was also supported by the 11 inch diameter GOX testing which was looking for passive techniques for combustion stability. An interesting footnote to that work was the conclusion that 'heat released from combustion of hydrogen gas in the dump plenum at an estimated mixture ratio of 120 also stabilized combustion in configurations that were otherwise clearly unstable.' This conclusion was also used in the design and development of Motor 2. [6]
Two HPDP tests published in the reference [10] show the effect of fins and no fins on multiport hybrid motors. These motors were tested with the same conical injector. The motor having fins in the forward dome had more fuel regress (19.64 lbm) than that of the motor dome without the fins (4.24 lbm), even if corrected for the burn time differences(~18 vs ~8 seconds). However, that additional head-end fuel regression did not result in an increased motor C* efficiency (both yielded 98%) or combustion stability, as judged by the chamber pressure average oscillation divided by average pressure (1.60% vs 1.60%). The conclusions that can be drawn from tables 4, 6 and 12 of reference [10] is that the impingement of LOX on the head end fuel fins can cause it to erode, but that additional fuel flow may not contribute to combustion stability or an increased C* efficiency.
The Motor 2 head end design that was eventually built and tested was similar to the patented design [12] (Figure 1 and Figure 7). It incorporated heater motors to start the main motor and provide heat to vaporize the LOX for combustion stability. An axial injector was designed for Motor 2 since Motor 1 used a conical spray pattern injector, and AMROC's patent [11] indicated that LOX impingement on the burning fuel surface could be a cause of the instability. The head end also incorporated a recirculation area in the front end, where gaseous oxidizer would theoretically recirculate and burn the head end fuel, generating even more heat.

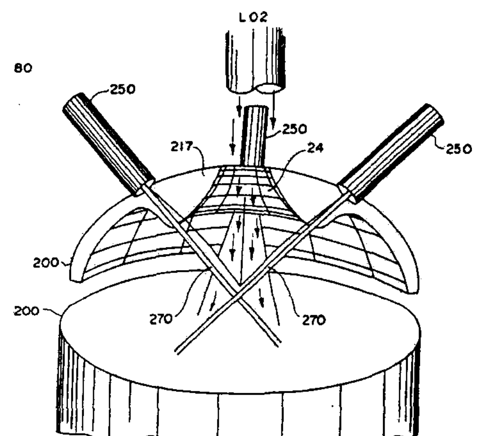

Figure 7 US patent 05794435

Ballistic Tests

Motor 1 Test 1

Motor 1 test 1 was the first of the 250K hybrids tested at Stennis Space Center and was conducted on July 9, 1999. This was the passive combustion stability design employing fins in the headend and a flow deflector over the center port. It was lit by TEA/TEB and exhibited unstable behavior (Figure 8). Due to an external

TEA/TEB system fire, the test conductors terminated the test prematurely. There was minor scorching of some of the ignition system. Calculations have shown that the requested TEA/TEB flowrate to motor was received even though some TEA/TEB escaped to the atmosphere. Subsequent testing of the TEA/TEB ignition system indicated failed pressure transducer diaphragms, which were over pressured due to water hammer causing the TEA/TEB to leak. Once the TEA/TEB, a phyrophoric liquid, came in contact with air, it burned.

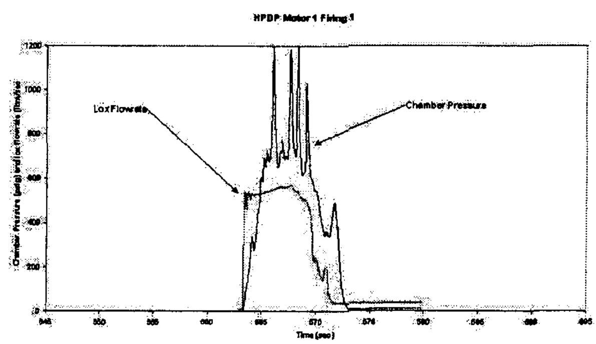

Figure 8 HPDP 250K Motor 1 Firing 1

Motor 2 Test 1

Motor 2 Test 1 was the first test of the active combustion stability system, with embedded heater motors in the head-end. The ignition system consisted of two banks of small gaseous hybrid motors embedded in the forward dome of the motor. The test was conducted on August 13, 1999. Ignition was smooth and combustion was stable (Figure 9). A small pressure blip that occurred during the first few seconds of the test was believed to be from the backlighting of one bank of the gaseous hybrid motors in the head end. Pretest checks indicated that the ignition system of one of the banks of gaseous hybrid motor was shorted out.

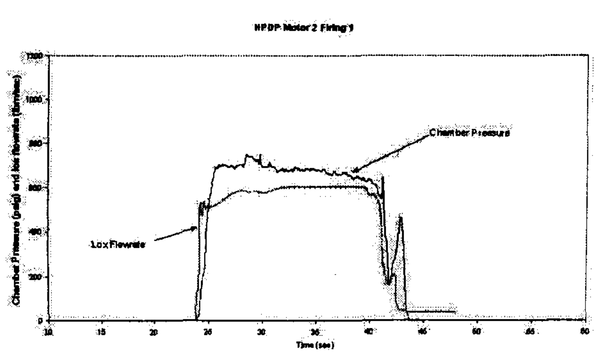

Figure 9 HPDP 250K Motor 2 Firing 1

Motor 2 Test 2

Motor 2 Test 2 was a refiring of the Motor 2 Test 1 hardware, except the nozzle from Motor 1 Test 1 was used. The test was conducted on September 9, 1999. The nozzles, by design, were refurbished between each test and the nozzle from Motor 1 test 1 was available and had eroded less that the nozzle from Motor 2 test 1.

Motor 2 Test 2 ignited smoothly, however large pressure oscillations were encountered during the burn (see Figure 10). It is believed the small gaseous hybrid heater motors, as they burned (the ports got bigger and the flux dropped which shifted the O/F), produced less heat to provide the necessary LOX vaporization and flame holding necessary for combustion stability.

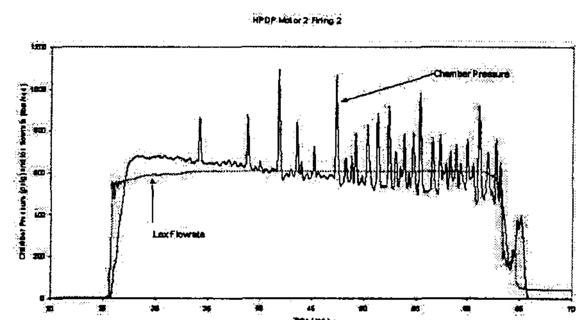

Figure 10 HPDP 250K Motor 2 Firing 2

Motor 2 Rework

Since the small gaseous hybrids for heater motors had burned till they were no longer able to provide a sufficient heat source and/or flame holding device, they were drilled out and recast in a slightly different configuration.

Motor 2 Test 3

Motor 2 Test 3 was reassembled using the refurbished nozzle from Motor 2 Test 1. The test was conducted on January 17, 2002 and exhibited a smooth ignition and steady pressure trace (see Figure 11). The small pressure disturbances/blips are believed to be from ejecta. Part of the recasting of the head end were found post test outside the motor.

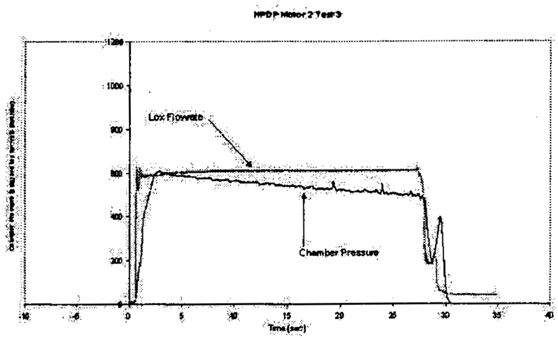

Figure 11 HPDP 250K Motor 2 Firing 3

Motor weights were calculated by three techniques during the 250K program. The first technique was to weight the components or sometimes the assembled motor on truck scaled (at MSFC and/or SSC). The second technique was system called the bore crawler. It used mechanical arms and fingers to measure the port geometry pre and post test. Data from that technique was used in a previous paper on the 250K hybrid. [13] A third technique was developed that used a laser to map the port area. The laser was drug thru the individual ports pre and post test and area of the ports at those locations were calculated. From that the motor weights were calculated. The data from the laser technique, indicating the port shape, can be seen in Figure 12.

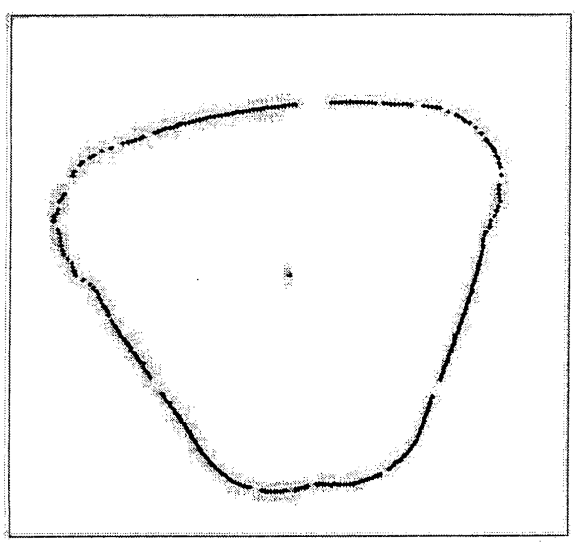

Figure 12 Laser Port Mapping Sample – Pretest Port

Average regression rate data the ports per test can be shown in Figure 13, Figure 14 and Figure 15.

There was a significant difference between the three weighing techniques, with the maximum percentage differences of techniques near 10%. This has lead to some uncertainty in the performance calculations. Another possible contributor to the uncertainty in the performance calculations is that the Cavitating venturi was never calibrated.

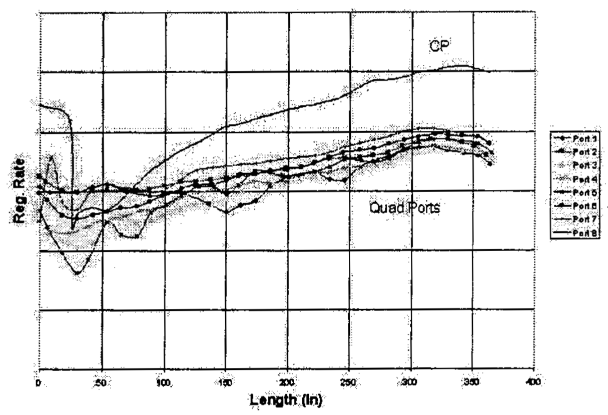

Figure 13 HPDP 250K Motor 2 Test 1 Regression Rates

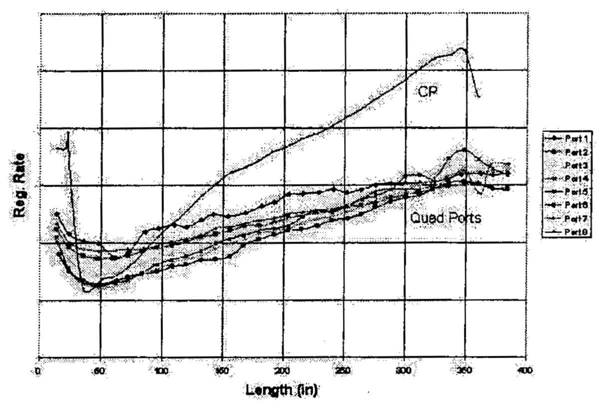

Figure 14 HPDP 250K Motor 2 Test 2 Regression Rates

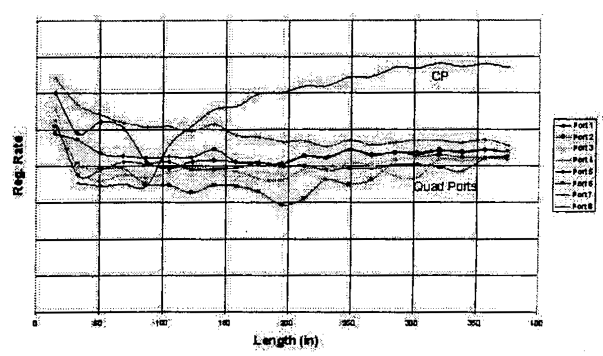

Figure 15 HPDP 250K Motor 2 Test 3 Regression Rates

Table 2. Average Motor Performance Parameters

Parameter	Motor 1	Motor 2		
	Test 1	Test 1	Test 2	Test 3
Thrust (lbf) - Vac	177136.9	186336.9	210065.5	195989.4
ISP VAC	250.0	248.6	276.9	263.9
ISP VAC EFF	0.77	0.78	0.90	0.92
Cstar	4,576.3	4,855.9	5,092.9	5,044.2
Cstar %	78.7	84.9	93.5	97.6
Global O/F	2.3	2.8	3.5	4.5
Duration (sec)	7.9	18.6	38.9	28.0
Chamber Pressure (psia)	594	625	600	542

CSTAR chart from Theoretical calculations with PC=600, Ae/A*=10 is shown in Figure 16. The test O/F and ISP/CSTAR calculations are from HPDP FINAL REPORT [17] with Laser mapping of Center port weights.

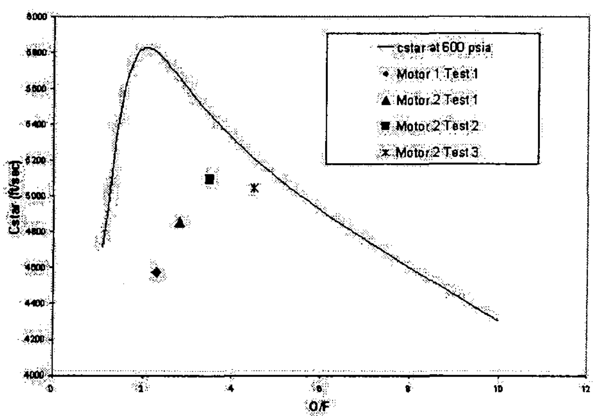

Figure 16 Theoretical Cstar vs Data

Performance Analyses

The global performance calculations for the motors are shown in table 2.

The high O/F ratios for the motor 2 tests can be attributed to two things – scale up from small hybrid rocket motor burnrates and the typical shift in O/F seen in hybrid motors. The 250K hybrid was designed based on a motor with a hydraulic port diameter of 2. The hydraulic port diameter of the 250 K was on the order of 4 times as large. Subsequent testing of the ¾ scale motor, a large single port quad motor, in the HPDP program provided a clue as to what would happen, an expected 30% reduction in recession rate[14]. Other work comparing small ports regression rates extrapolated to larger ports showed an error in the regression rates greater than 10%[15]. Reduction in the fuel flow rate affects the O/F, chamber pressure and thrust.

Stability of the tests can clearly be seen in the spectrograms of the test data Figure 17, Figure 18, Figure 19, and Figure 20. The spectrograms show the Power Spectral Densities over time, with the amplitude at the right representing the logarithmic magnitude of the oscillations. The tests where the heater motors provided stability are easily recognizable. Another way to look at the stability is shown in Figure 21, Figure 22 and Figure 23, which show the filtered composite normalized by average pressure. The bandpass filter is between 5 and 500 hz to remove the non-acoustic response. The oscillations upstream of the injector show the noise from the cavitating venturi. The two pressure blips in Motor 2 test 3, which are believed to be ejecta show up quite well. The unstable nature of motor 2 test 2 is also quite evident in Figure 22, with the RMS excursions denoting an excitation in acoustic activity concurrent with the low frequency events.

General

A multiple port grain configuration was used in 250K hybrid motors due to the low fuel regression rate requiring a lot of surface area to generate the fuel. The head end and the aft end attached to the each side of the main fuel grain represent a pre-combustion chamber for heating and vaporizing LOX and a mixing chamber for completing reaction of unburned fuel with oxidizer, respectively. One explanation for the chamber pressure oscillations that occurred in Motor 1 Test 1 and Motor 2 Test 2 may be because of different fuel regression rates in the multiple chambers (quad ports and center port) resulted from uneven LOX distribution, incomplete vaporization of LOX at lower temperature, and not thorough combustion in the mixing chamber. The operation of the heater motors in Motor 2 tests 1 and test 2 seems to have corrected for this phenomena. However, incomplete reaction of fuel to oxidizer in the ports and in the aft mixing chamber may have lowered the motor combustion efficiency in all of the motors.

In order to prevent unstable combustion in hybrid motors, flow and combustion conditions under the lower temperature of LOX and very oxidizer rich environment at the forward end of the fuel grain need to be precisely determined to establish a proper flame front, which keeps the motor stable. A proper flame front was demonstrated using the hybrid heater motors on Motor 2 tests 1 and 3.

Performance

Motor performance in terms of the C* efficiency yields 78 to 97% while in terms of Vacuum ISP yeilded reveals 77-92%, implying a fuel regression rate in conjunction with unburned fuel or improper mixing. Based on the bore crawler data, the amount of fuel regression in Motor 1 indicates severe difference from each port. [13] The amount of regressed fuel of the quad ports vary from 155 lbm to 220 lbm with the center port of 112 lbm, which is equivalent to the minimum regression of the quad ports after compensation of the cross sectional area ratio. The low regression of the center port in Motor 1 is believed to be because of the existence of the flow deflector, causing a tortuous path for the lox to take. In contrast in Motor 2, fuel regression in the center port exceeds the maximum regression in the quad ports, implying a larger amount of oxidizer flowing through the center port than the quad ports. Motor 2's axial injector directs the lox directly toward the center port.

Pressure

Motor pressure-time characteristics in Figure 8, Figure 9, Figure 10, and Figure 11 exhibited both stable and unstable combustion, especially large amplitude pressure oscillation in the Motor 1 test and the second test of Motor 2. The averaged chamber pressures of Motor 1 and Motor 2 lay between 542 and 625 psia, far less than the designed average pressure of 750 psia at LOX flow rate of 600 lbm/sec, as given in Table 1 and 2. In Motor 1 test and the second test of Motor 2, severe chamber pressure fluctuations (spikes) were noticed throughout the tests. Relatively small pressure peaks at the ending period are due to the onset of gaseous nitrogen for shutdown. In Motor 1 test 1 and Motor 2 test 2, each pressure spike using the high-speed data acquisition system (12500 data/sec) revealed similar characteristics of pressure build up and discharge processes. Magnitude of the spikes are generally close to the theoretical maximum operating pressure level while some surged as much as twice the mean pressure. Decrease in pressure timewise is expected, due to the throat erosion, lower flux level as the ports open up with subsequent lower fuel regression rates changing the O/F ratio.

C*

One of the ballistic parameters that quantifies motor performance is C*, a characteristic velocity shown in Fig. 3. The ratio of actual C* to the theoretical maximum C* from the industry standard thermochemistry code represents motor efficiency [13]. The C* efficiency in the figure indicates that a significant amount of fuel has not released all of its energy inside of the motor as previously experienced [18], as shown in Figure 16. Also, the C* efficiency seems to be higher in the motors with motor with higher O/F ratios. This phenomena has been observed in single port subscale motors.[19] Possible causes in the 250K hybrid may be than the same mixing in the aft end of a motor may cause more combustion in an oxidizer rich environment or that the lower flux levels provided more reaction time in the ports and mixing chamber.

Regression rate

Direct measurement of the port circumferences were attempted using both mechanical (Crawler) and laser measuring devices to calculate the amount of fuel regressed. Figure 13 shows a typical pre-fire quad port configuration and Figures 14-16 show the average fuel regression rate of individual ports of Motor 2 acquired by the laser device. Noticed is that the regression profiles of the quad ports are not coincident with the result from the Crawler [13]. Note that direct impingement of oxidizer flow affects higher regression rate at the port entrances and a significant drop in the center port implies use of the cylindrical flow reducer placed in the entrance, as shown in Figure 13, Figure 14, and Figure 15.

In general in Motor 2, the regression rate increases monotonically lengthwise except the third test where the rate for the quad ports stay relatively in constant. From this result, it is obvious to consider dependency of the LOX flux level, motor length and port diameter in a fuel regression correlation.

Stability

A hybrid motor differs fundamentally in terms of combustion behavior compared with solid and liquid rockets in that the O/F ratio has an axial dependency. Historically, both acoustic and non-acoustic instabilities related to the motor geometry were encountered during the development of a large scale hybrid rocket motor. It is believed that the relatively cold flow of oxidizer in the head end causes pressure oscillation and thus methods of adequate LOX vaporization, reduced droplet size, and use of flow deflector were introduced to suppress combustion instabilities [18]. Significant amount of efforts were given to evaluate combustion instability during the hybrid motor development in terms of vortex shedding [6] and diffusion flame movement [20], but complexity of the multi phase diffusion flame combustion dynamics in the turbulent reacting flow has not been fully disclosed yet.

From the instability point of view, it is not clear from Figure 13, Figure 14, and Figure 15 that, excluding deviation in the quad ports, significant difference in the regression rate at the center port from those at the quad ports in the second test leads to unstable combustion, since Motor 2 tests 1 and 3 were stable.

Variation of local O/F ratio in the combustion chambers may be a key factor for determining the hybrid motor stability. And multi-port with a one head end lox injector configuration having pressure variation between combustion ports from uneven distribution of oxidizer could be additional source for the instability by developing pressure oscillation in tangential mode at the port entrance. The center ports in Motor 1 and Motor 2 are examples for the uneven distribution cases. Apparent local O/F ratio in the center port of Motor 1 seems lower than the optimum value from the entrance leading fuel rich condition through the entire port length. It could be resulted from the existence of the flow deflector. In contrast to Motor 1, the center port of motor 2 has much higher oxidizer level at the inlet, allowing continuous increase of the fuel regression rate downstream with ongoing advantage of higher temperature. Even an excessive amount of LOX at inlet might cause the port entrance to be under two phase, liquid and gas, combustion.

AMROC apparently experienced the same situation with different regression rates in the CP and outer port and designed around it, since their large scale motors used only quad ports and blocked the center port. The blocked center port also acted as a splashblock, which increased the residence time in the forward chamber [3] [5].

A possible cause for pressure fluctuation in these motors is the difference of the fuel regression rate between upstream and downstream in the chamber and/or continuous throat erosion. A traveling wave in the combustion chamber disturbs turbulent mean flow field characteristics in the ports, which enhances mixing of unburned fuel and oxidizer in a periodic fashion and fuel regression rate by more heat transfer to the fuel. From this point gas filling and discharging sequence is being unbalanced until the chamber pressure reaches the maximum operating status. Continuous fuel regression and throat erosion disrupts the continuity by discharging more gases resulting in lowering the chamber pressure. This single port combustion phenomenon, along with the interaction with the other ports in a multiport design, could have lead to the instability caused in Motor 1 Test 1 and Motor 2 Test 2.

Nozzle

It was obvious that the reaction of carbon in the throat with hot oxygen in the exhausting gases accelerated the throat erosion. Real time erosion rate of the throat is not available because only pre- and post measurement were conducted. The results showed a higher erosion rate than predicted from the early subscale test data, with low O/F ratios [21]. However, later subscale tests with the same material indicated a similar erosion rate.[9] Different characteristics of the gas flow from the individual combustion ports caused irregular throat erosion aligned with the ports. This has been seen before in tests with multiport grains [21] and was expected.

Figure 24 shows thrust versus chamber pressure ratio for Motor 2 as an indirect indication of the throat erosion characteristics. The slope of the curve in the figure correlates with nozzle erosion rate. Note that discontinuities in the second test are due to the pressure peaks where instantaneous changes of the thrust coefficient, a dependent parameter on chamber pressure, occurred. Ignoring the discontinuities, throat erosion rate remains relatively constant, excluding the transient period of initial heating and charring at the beginning stages.

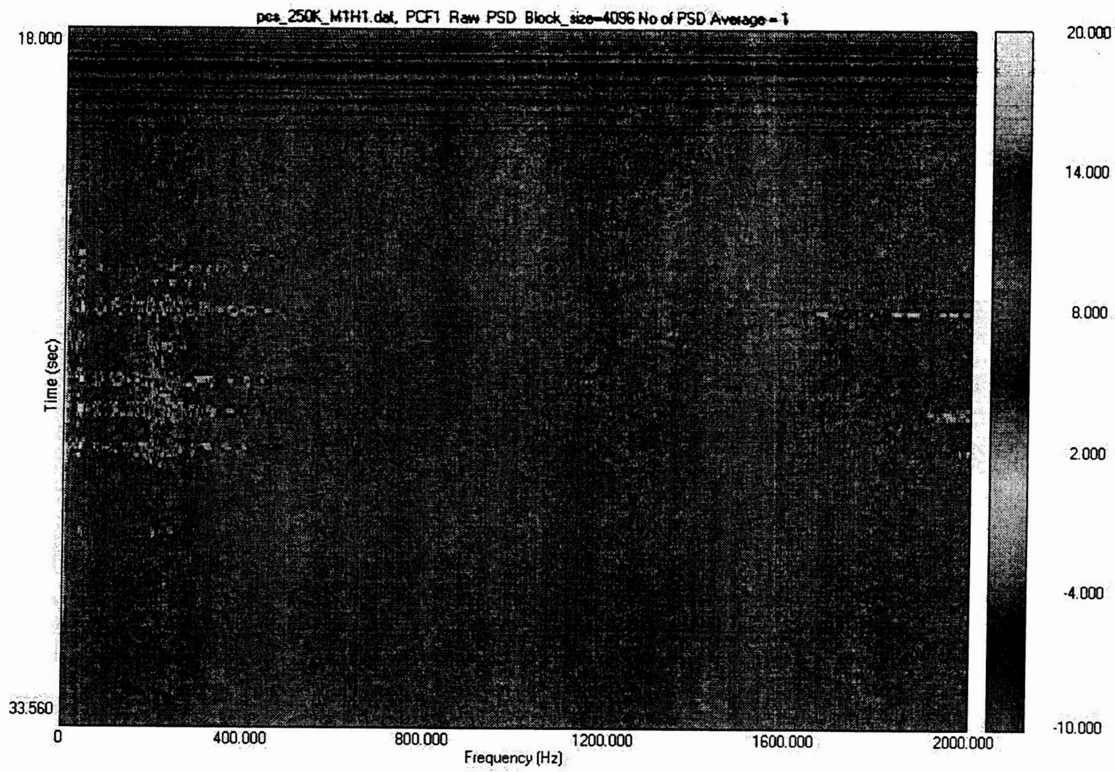

Figure 17 Motor 1 Test 1 Fwd PC Spectrogram

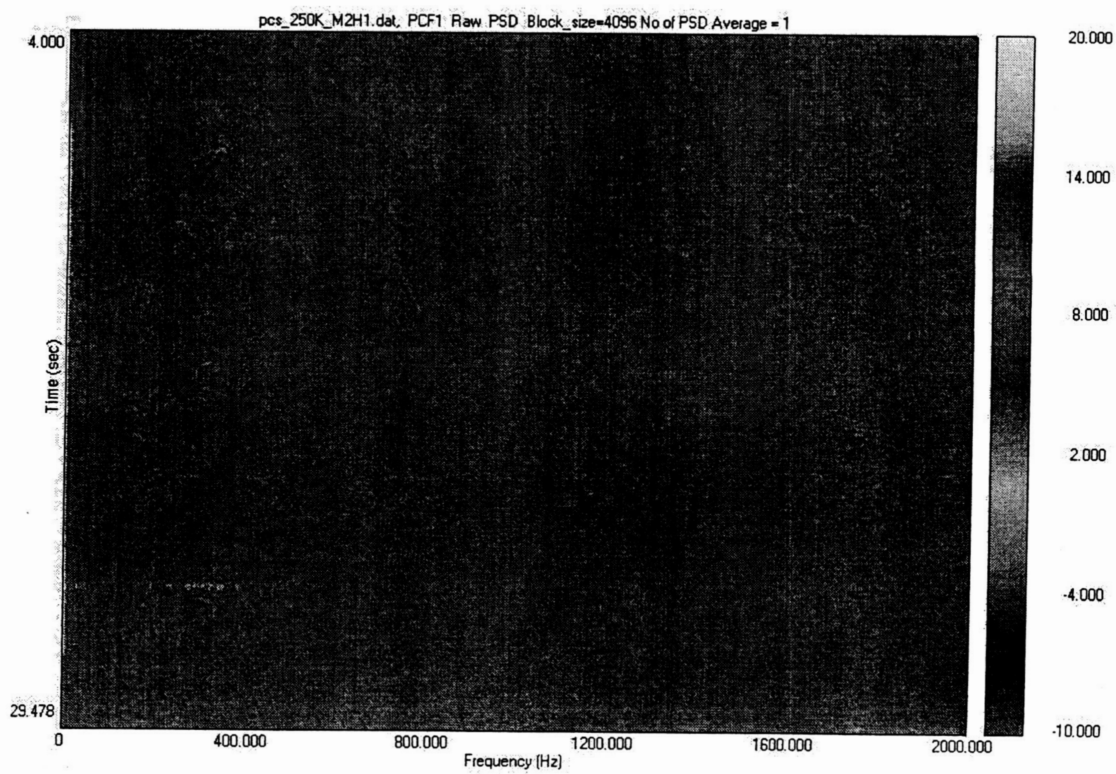

Figure 18 Motor 2 Test 1 Fwd PC Spectrogram

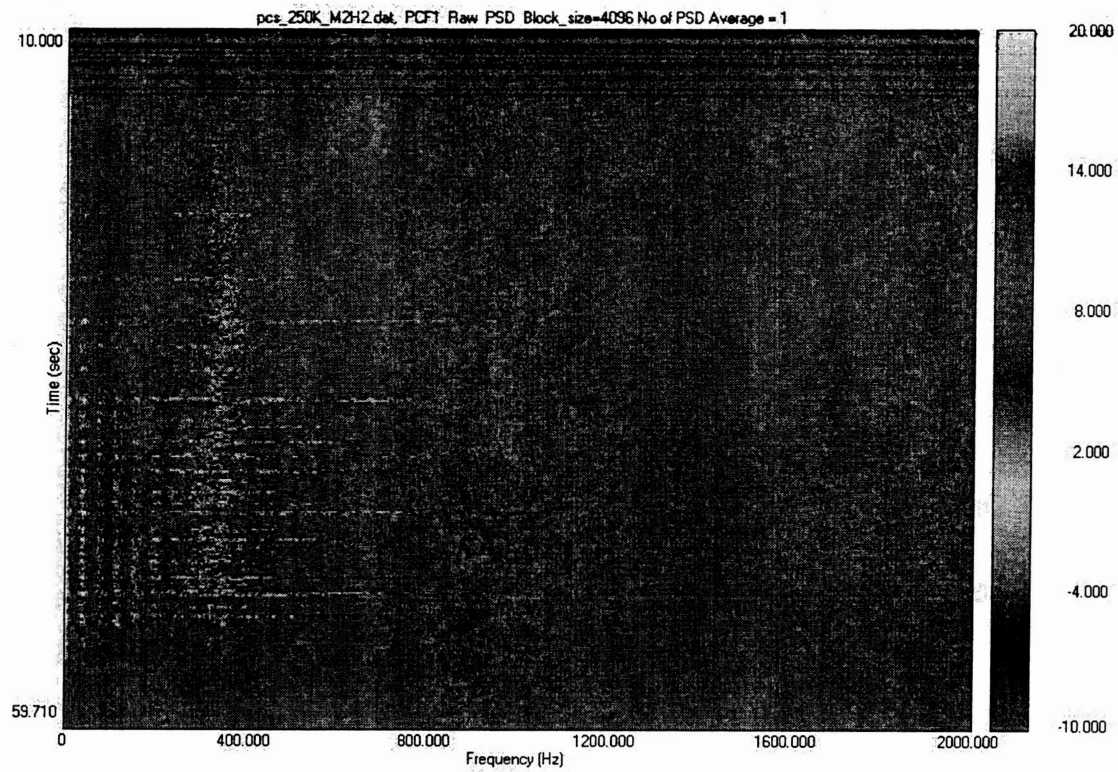

Figure 19 Motor 2 Test 2 Fwd PC Spectrogram

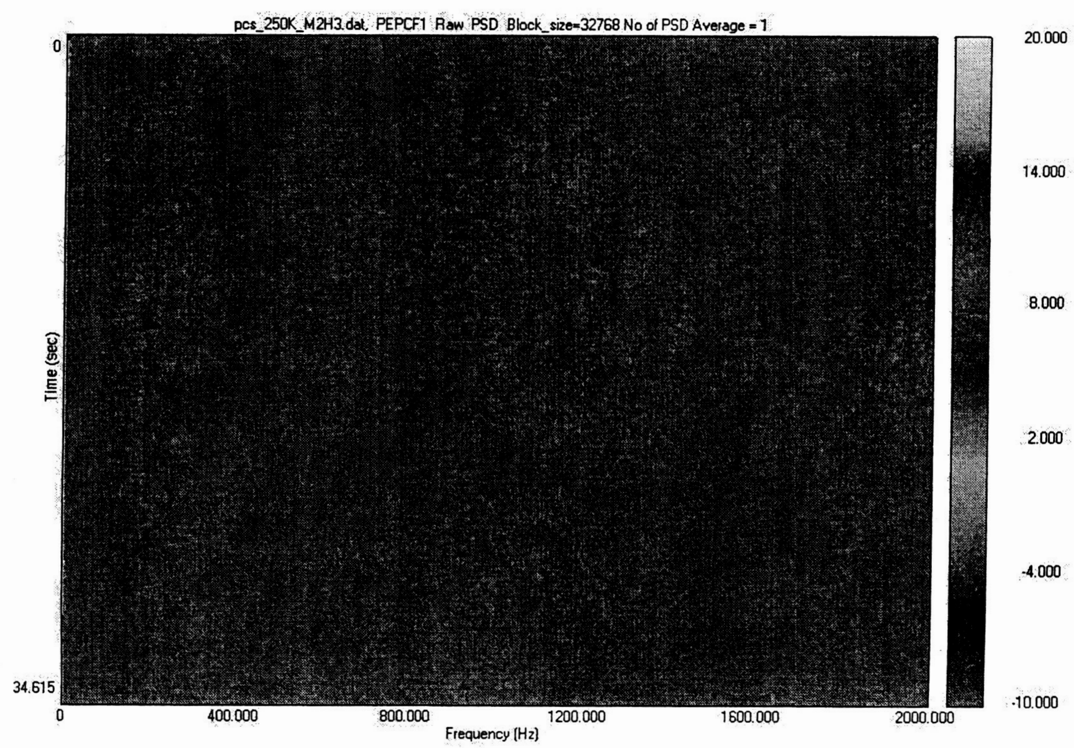

Figure 20 Motor 2 Test 3 Fwd PC Spectrogram

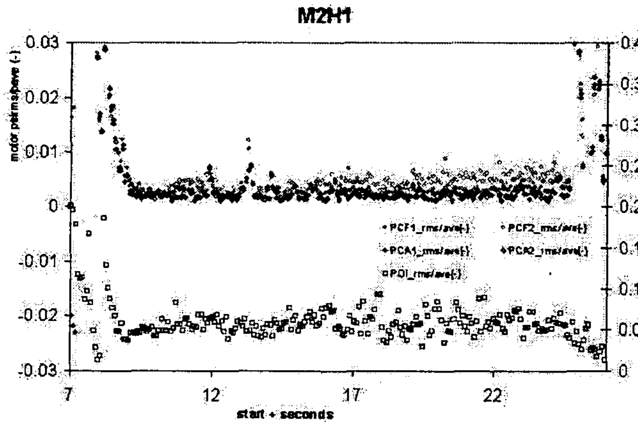

Figure 21 Filtered composites normalized by ave pressure M2T1

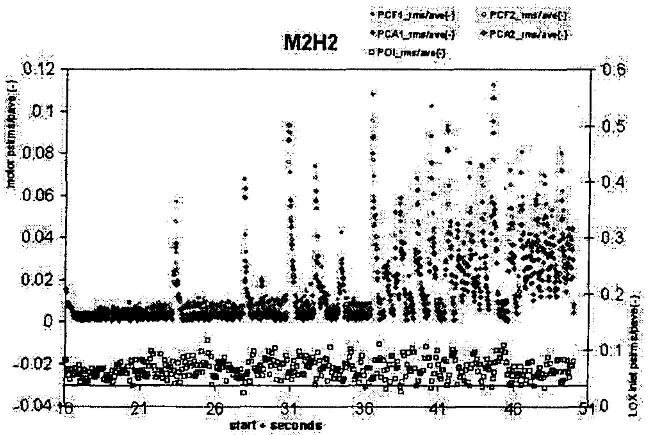

Figure 22 Filtered composites normalized by ave pressure M2T2

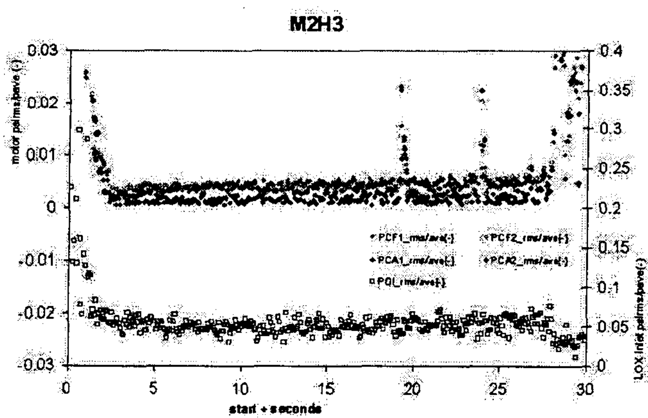

Figure 23 Filtered composites normalized by ave pressure M2T3

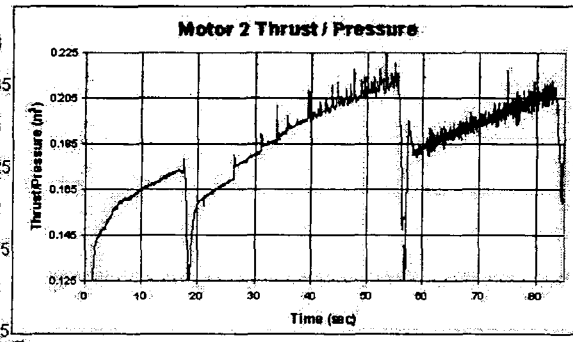

Figure 24 Motor 2 Tests Thrust/Pressure

Conclusions

1. Motor 1's passive design was unstable. This doesn't imply that all hybrids of this size will require an active heat source in the front end of a hybrid, but this one was unsuccessful in achieving stable performance.
2. Motor 2 was stable during tests 1 and 3, but drastically unstable in test 2. The concept to add heat in the head end of the motor worked, but the design solution tested could not provide stability for the full 80 second duration. Another design solution will have to be worked for future full duration testing.
3. Scale up from small hybrids to large hybrids, as demonstrated by the achieved regression rates and lower than expected chamber pressures, was not done effectively on this program. Scale ups should be made from the largest port data possible.
4. The nozzle material selected for this program eroded greater than the design parameters.
5. HPDP 250K testing, in some fashion, should continue. The ISP and stability observed in these tests provide an incentive to further improve this simple rocket system. Motor 1's grain has been fired for only 8 seconds and there have been several suggestions put forward for additional testing.

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