A Labscale Hybrid Rocket Motor for Instrumentation Studies

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ABSTRACT

An interest in plume spectroscopy led to the development of a labscale Hybrid Rocket Facility at the University of Arkansas at Little Rock (UALR). The goal of this project was to develop a reliable, consistent rocket motor test-bed for the development of plume spectroscopy instrumentation. Hybrid motor technology was selected because it has proven to be safe and inexpensive to operate. The project included the design and construction of the labscale hybrid rocket motor, the supporting facility, the instrumentation and computer control of the motor, and the characterization of this particular thruster, including the regression rate of hydroxyl-terminated polybutadiene (HTPB) fuel grains. For plume spectroscopy experiments, the fuel is doped with metal salts, to simulate either solid motors or liquid engines. It was determined the labscale hybrid motor produces a reliable and consistent plume, resulting in an excellent tool for the development of plume spectroscopy and other instrumentation.

Keywords: hybrid rocket motor, plume spectroscopy, engine health, ground testing, rocket diagnostics

Introduction

In recent years there has been an increased interest in engine health monitoring, particularly by observation of the rocket plume. At NASA-Stennis Space Center, Space Shuttle Main Engines (SSME) are rebuilt after every flight. Several studies have indicated that severe engine wear can be detected by engine plume diagnostics, and the need for these expensive rebuilds may be eliminated.[1] In some types of rocket motors, especially solid motors, toxic combustion products may be produced, so it is also environmentally important to monitor emissions from rocket plumes.

The University of Arkansas at Little Rock has been developing low cost, rugged instrumentation for plume spectroscopy for the last few years. UALR has performed joint work with NASA-Stennis, Hercules Aerospace and other aerospace companies. Testing instrumentation at other facilities, which have firing capabilities, can be accomplished; however, this is expensive, time consuming, and inconvenient, as firing schedules are usually very rigid. The need for a system to easily test new instrumentation and techniques to monitor rocket plumes provided the motivation to develop this labscale hybrid rocket motor facility at the University.

The labscale Hybrid Rocket Facility provides a significant capability for instrument testing, especially for plume spectroscopy instrumentation. Most current diagnostic work is aimed at measuring emissions from solid motors or engine component degradation in liquid engines. Facilities to test plume-monitoring instrumentation usually consist of a thruster of one of these two types. However, hybrids offer greater safety, reliability, and lower operating costs. Because UALR has the facilities to cast fuel grains, these can be doped with different metal salts for seeding the plume. This is necessary for simulating solid motors or liquid engine component degradation.

The project included the design and construction of a labscale hybrid motor, instrumentation for the motor, the design and construction of gas flow system to support the motor, a computer control system, and a data acquisition system. This facility was constructed on the University campus and included areas for plume monitoring instrumentation.

To test the level at which this hybrid facility meets the needs of the project, experiments were conducted to determine the quality and reliability of the plume produced, as well as the spectral characteristics of the plume when seeded. Experiments were conducted to determine the combustion stability of the motor with HTPB fuels and a test matrix developed to determine the regression rate of the HTPB fuel over a range of oxidizer flows. The plume was also seeded with metal salts and spectral data was collected in the UV-Vis, as reported in a separate paper.[2]

Conversion Units

1 lbm = 1 pound mass = 454 grams
1 lb = 1 pound = 454 grams
1" = 1 in. = 1 inch = 25.4 mm
1 psia = 1 pound per square inch = 0.145 kpa

Theory of the Testbed Facility

The test facility as constructed was based loosely on the Diagnostic Testbed Facility (DTF) at NASA's John C. Stennis Space Center and other ground based test units, such as those for solid motors. Now a part of the Component Test Facility, DTF was designed to provide a testbed for development of liquid engine plume diagnostic instrumentation. A 1,200 pound thrust liquid oxygen/gaseous hydrogen thruster was used as the plume source for experimentation and instrument development. Studies have been performed to ensure the DTF thruster has been optimized to produce a plume with temperature conditions as much like the plume of the Space Shuttle Main Engine (SSME) as possible. The engine is equipped with a plume seeding device, which allows liquid seeding materials (dopants) to be injected directly into the combustion chamber.[3] These materials simulate engine component failures, such as occur in bearings and other structural elements.

Comparatively, the Hybrid Rocket Facility at UALR provides a testbed for the development of rocket propulsion system exhaust plume diagnostics instrumentation for solid motors and liquid engines. A 50 pound thrust hybrid rocket thruster is used as the plume source. It operates on gaseous oxygen and hydroxyl-terminated polybutadiene solid fuel. While the plume visually looks more like a solid motor plume, the combustion products are similar to a liquid engine using a kerosene fuel and liquid oxygen. The fuel grain, during casting, can be loaded with metal salts to provide the same seeding capabilities as DTF. The facility also was designed to simulate solid rocket motors. The fuel can be loaded with chloride salts to produce hydrogen chloride emissions.

Design and Materials

The facility consists of the labscale hybrid motor, the gas flow control system, the computer controlled operating system, the computer data acquisition system, and the instrumentation on the motor and other systems.

The initial step was the design of the hybrid motor thruster. Several specifications needed to be met with this motor. It needed to be fairly small; this would cost less to build and less to operate while offering greater safety. Most labscale motors consist of fuel grains 2 inches in diameter or less, and this size range fits the needs of this project.

Second, the motor needed to be capable of simulating the characteristics of larger motors. This scalability is necessary because most plume spectroscopy instrumentation is designed to operate on actual propulsion systems. To simulate those motors well, the hybrid thruster was designed with the capability of producing chamber pressures up to 500 psia, giving plume temperatures and other characteristics similar to larger motors.

Also, for spectral purposes, the oxidizer to fuel (O/F) ratio would need to be varied from below stoichiometric to well above stoichiometric for the HTPB fuel. To accomplish this, the oxidizer flow has a maximum mass flow of 10 pounds per minute of gaseous oxygen. This allows firings under a wide range of chamber pressures and oxidizer to fuel ratios. The motor design has a fuel grain 2 inches in diameter and 10 inches in length. It starts with a central cir-

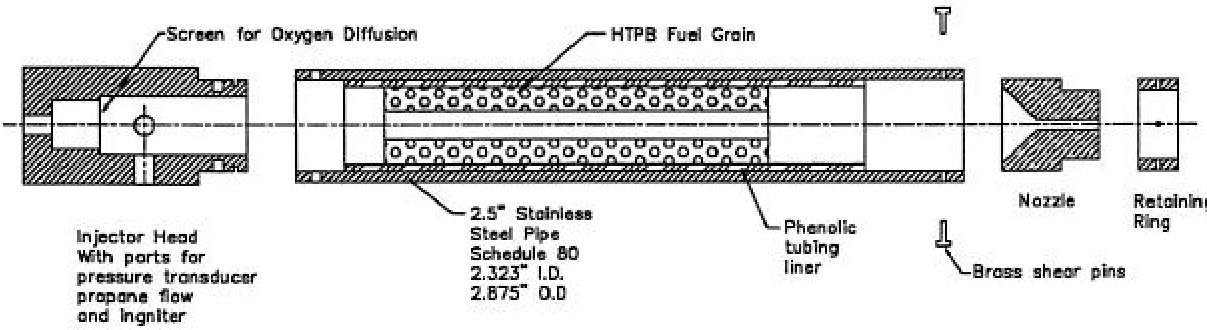

Figure 1. Layout of the labscale hybrid rocket motor.

cular port 0.75 inches in diameter. This size fuel grain, coupled with the oxidizer flow rates attainable, can give O/F ratios from 1.5 to 4.5. This is ideal because HTPB burns stoichiometrically to CO and H_2O at an O/F ratio of 2.074.

The motor design consists of two main sections, the head assembly and the chamber body. The specifications for the mechanical design of the chamber body included the following design goals. The chamber was designed for a maximum firing pressure of 500 psia. The nozzle was designed to eject at 1000 psia in case of chamber over-pressurization. A 3 times safety factor was needed for pressure tolerance on the chamber body (3000 psia). This required a section of type 304 stainless steel, 2.5 inch, schedule 80 pipe. In addition to the 10-inch fuel grain, the chamber body would also have to house the nozzle and two chambers, one fore and one aft of the fuel grain. The design is shown in Figure 1. The head assembly is machined from a type 303 stainless steel round. This unit includes a diffusion screen, oxidizer flow/nitrogen purge inlet, propane ignition inlet, igniter inlet, and chamber pressure transducer port.

The nozzle is machined from a section of graphite and is 2.5 inches in length, held in place by a steel retaining ring and brass sheer pins. The fore and aft chambers are lined with silica phenolic tubing used as an ablative insulator. Paper phenolic tubing is used as a sleeve in casting the fuel grain and is left on the grain during firing, which eases assembly and disassembly. For casting, the sleeve is held in a Teflon jig, with a Teflon coated rod as a central port mandrel.

Gaseous oxygen as oxidant, nitrogen for purging, and propane for ignition are needed to operate the motor. The oxygen and nitrogen are each supplied in a standard K or T cylinder and the propane in a standard "gas grill" bottle. Each gas line consists of a pressure regulator on the cylinder, a purge valve, a pressure relief valve or check valve, an electronically controlled shutoff valve, and a flow-metering device. The gas flows are set manually prior to firing by adjusting the tank regulators. The flows are started and stopped electronically using solenoid valves, allowing computer control of the firing sequence. The oxygen flow system has the capability of handling a mass flow of up to 10 pounds per minute at pressures up to 1000 psia. Flow is initiated using a pneumatic shutoff valve that is operated with nitrogen, controlled by a solenoid valve. The mass flow is controlled using a sonic flow nozzle and setting the proper regulator pressure. The actual mass flow is determined by measuring the pressure and temperature on the upstream side of the sonic flow nozzle. A pressure transducer and thermocouple are utilized to make these measurements. The flow of both the nitrogen and propane are set using regulating valves. A schematic of the gas system is show in Figure 2.

Instrumentation

The function of the entire firing sequence is controlled and monitored by computer. This system consists of a 486DX-33 MHz computer (Gateway, Inc.), a 12-bit analog-to-digital conversion board (Computer Boards, Inc.), which includes digital input/output ports, an analog

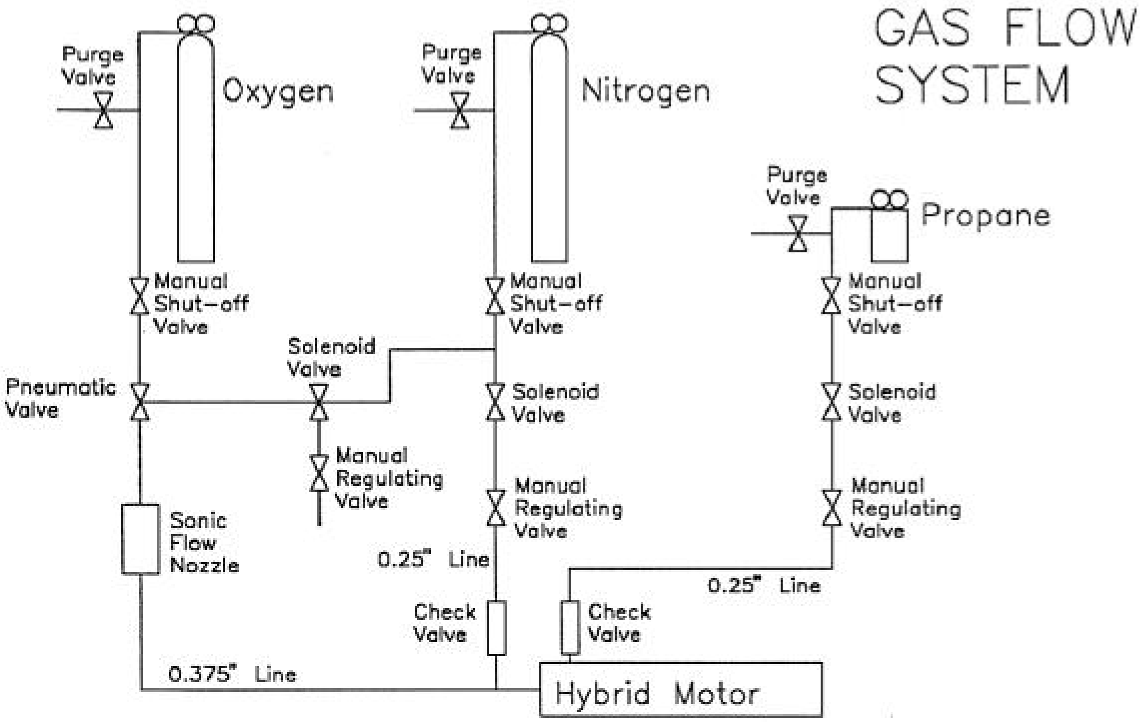

Figure 2. Gaseous materials flow system.

isolation board, and a solid-state digital input/output board.

The analog-to-digital board is installed in the computer and is connected to the remote analog isolation board. The isolation board accepts analog inputs from two pressure transducers (Keller PSI) and four thermocouples. It is capable of handling up to 8 differential inputs. One pressure transducer (1100 psia maximum) measures the oxidizer pressure on the upstream side of the sonic flow nozzle and one J type thermocouple takes the temperature at this position. The other pressure transducer (1000 psia maximum) measures the chamber pressure of the hybrid motor. The output from these pressure transducers is 0 to 5 volts DC. The other three temperature inputs are from K type thermocouples and can be positioned where needed on the motor or test stand. All thermocouple inputs are fed into 5B type analog isolation modules on the analog isolation board. These modules linearize and cold-junction compensate the thermocouple signal. The output from these modules is 0 to 5 volts DC so that they can be input directly to the analog-to-digital conversion board in the computer.

The digital input/output section of the board controls the gas flow system and the ignition pulse. The digital output lines go from the board in the computer to the solid-state digital input/output board. This board contains up to eight isolation modules that can control AC and DC voltage lines. Three of these control AC lines that operate the solenoid valves that control the gas flow. A fourth line controls a DC voltage line that is the igniter pulse line.

The computer firing control system consists of a graphical user interface screen, shown in Figure 3, with which the operator can control and observe all functions of the motor. Functions that can be controlled from the interface are the operation of the gas handling system, the firing duration (from 3 to 10 seconds), and the start of events for the automated firing sequence. Data is collected at 25 hertz per channel. While this is relatively slow, it is sufficient for a feed back loop to operate the hybrid motor and allows real time parameter display for the operator. The real time display includes: chamber pressure, upstream oxygen pressure, upstream oxygen temperature, oxygen mass flow rate, and the temperature at 3 separate points on

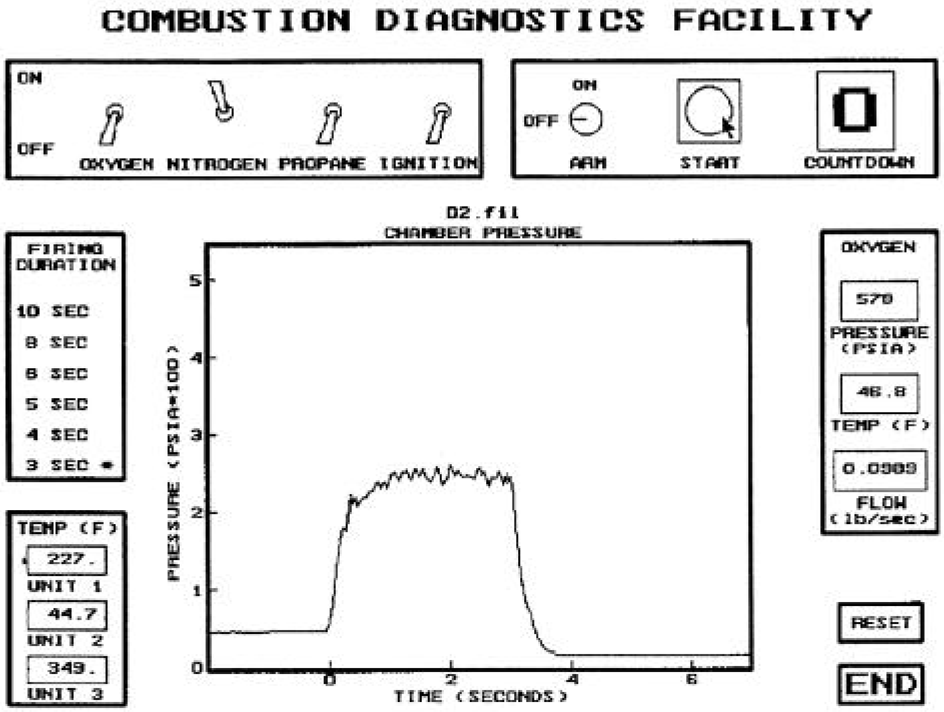

Figure 3. Graphical user interface for the Labscale Hybrid Rocket Motor Testbed Facility.

the motor. A thrust measurement can be included in the future, but was not required for the spectral monitoring experiments.

Data is also collected on a separate 486DX-33 (assembled in house) computer that is dedicated to this purpose. It also uses a 12-bit analog-to-digital converter board (Computer Boards, Inc.) installed in the computer. This board collects pressure data at 1000 hertz per channel, while temperature data is collected at 100 hertz per channel. This data acquisition system provides high-resolution data that is stored to ASCII data files. This data can then be analyzed and plotted at a later time. This system is controlled, after initial operator setup, by the firing control system, allowing greater ease of use.

Safety

Safety considerations were of the utmost importance since this facility was set up on the UALR campus. Safety measures were also designed directly into the facility itself. The first was the mechanical design of the hybrid motor. The maximum operating chamber pressure was designed to be 500 psia. The nozzle assembly is held in place with brass sheer pins and is designed to eject if the chamber pressure exceeds 1000 psia. This would dump all chamber pressure. The body of the motor is designed to handle pressures up to 3000 psia.

The gas flow system utilizes normally closed shutoff valves, so that in the case of a power failure, all gas flow is stopped, terminating combustion. Check valves are used on the nitrogen and propane lines to prevent any over-pressurization from the combustion chamber. The oxygen gas line is designed to handle pressures in excess of 2500 psia. It also contains a pressure relief valve that is set for 1250 psia.

The computer control system has a feedback loop incorporated into the software. This checks the chamber pressure 25 times a second. If the pressure is over a preset level, the oxygen flow to the motor is terminated. There is also a manual override switch between the computer control and the solenoid valves. This remains in the off position until a few moments before the firing sequence is begun. As a final step, the entire keyboard acts as an emergency shutoff.

Pressing any key during a firing will stop the oxidizer flow to the motor. If the computer control system should fail, but the rest of the power remains on, the manual override switch to the solenoid valves can be used to stop the oxidizer flow.

Experimental

After construction of the labscale hybrid motor, initially manually controlled firings of the motor were performed, using Plexiglas (polymethyl methacrylate) fuel grains. The permanent facility had not yet been constructed, so these firings were done to assure proper function of the mechanical aspects of the motor design. Once the entire facility was completed, testing was performed to assure proper functioning of all parts of the system. The parts included the gas flow system, the instrumentation of the motor, the computer control system, and the data acquisition system. The motor was first tested to see if the ignition system was performing as intended. The ignition system was designed to use a stream of propane injected into the oxidizer flow in the motor head assembly. This was ignited by a small electric match. The motor was test fired several times to assure the combustion stability of the HTPB fuel. In general, any changes in HTPB fuel formulation or control system configuration were followed by a series of low oxidizer flow, low chamber pressure tests. After these tests, a through examination of all low pressure data and motor components was followed by firings at increased oxidizer flow and chamber pressure, up to the desired 500 psia level.

The first experimental objective was to characterize the regression rate of the HTPB fuel grains. The regression rate of the fuel in a hybrid rocket motor can be given by the general equation:

$$r = aG_o^n \tag{1}$$

where r is the regression rate in inches per second, a is a constant including the blowing coefficient, G_o is the oxidizer mass flux (the oxidizer mass flow divided by the port area), and n is the regression rate pressure exponent.[4] A test matrix was developed to establish the values of a and n, and hence, the regression rate of HTPB fuels in this hybrid motor. This was accomplished by running the motor at various oxidizer flow rates, from about 2.5 to 10.0 pounds per minute of oxygen, with the regression rate of the fuel being measured. The regression rate is particularly important for further work when the plume is seeded. The seeding material is incorporated into the fuel grain, so that the final concentration of material in the plume will depend on the oxidizer mass flow and the regression rate of the fuel.

A series of 30 firings were completed, using six fuel grains. Each grain was fired either four or six times at three seconds per firing. It is important to keep the firing duration short, as the regression rate varies with the central port diameter. However, the firing duration also needed to be long enough to reach stable combustion for the data to be valid. Experimental results showed a three second firing duration to be a reasonable comprise to meet the two criteria. The fuel grains consisted of R45 HTPB, Desmodur N100 curative, and a few drops of a tin-based catalyst (no effect on spectral output). Normally 15% by weight N100 was used. No opacifier was added to the fuel grains used in the regression rate study. Havaflex T.A.-117 (Ametek) ablative was applied to the ends of the fuel grain to prevent end grain burning. This is important since the post firing port diameter is determined by the weight loss of the grain. Tests with and without ablative showed that end grain burning could contribute to errors in the measurement. While these errors are small, it was important for characterizing the motor to have the highest confidence levels possible. Future studies may not require this ablative, depending on acceptable error.

A second part of the overall project, which is not included in this paper, was to conduct a preliminary study and characterization of the baseline spectral emissions of the plume in the ultra-violet-visible (UV-VIS) region and the infrared region (approximately 200 nanometers to 15 micrometers).[2] That study included seeding the plume with metals and observing plume emissions in the UV-VIS region and determined that metals can be detected at low levels with good precision. This indicated that the

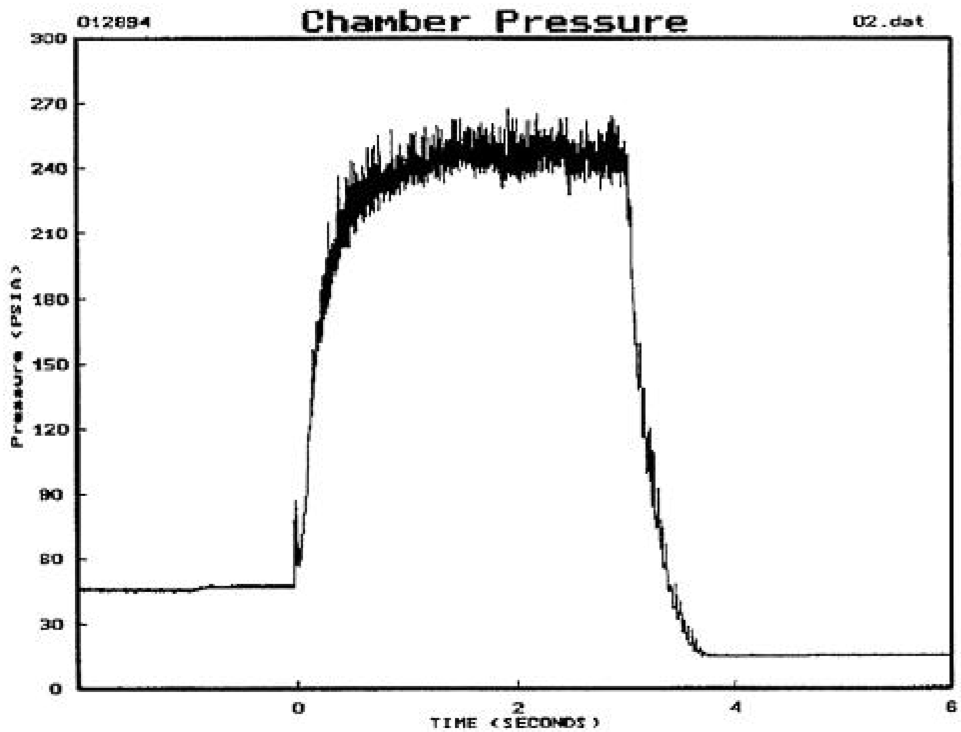

Figure 4. Chamber pressure data from the hybrid motor using HTPB fuel.

design was a stable platform for plume spectroscopy studies.

Results and Discussion

Construction of the labscale hybrid motor was completed in January of 1993. The motor was set up on a temporary test stand and fired using the Plexiglas fuel grains. Since this was set up on a temporary test stand, no propane was available for ignition. A different ignition system was utilized consisting of a small hobby rocket motor with a firing duration of 250 milliseconds. This was arranged so that the oxygen flow would be initiated, then the hobby rocket motor fired into the chamber upstream of the fuel grain, and ignition achieved. The ignition system worked very well. Eight firings were completed at low chamber pressures, below 200 psia. These firings demonstrated that the motor functioned as predicted, that the design of the motor was sound, and satisfied university and state safety officials that a rocket motor could safely be fired on campus.

The permanent facility was completed in September of 1993. All aspects of the facility were checked, including the gas flow system, the instrumentation of the facility, the computer control system and the data acquisition system. This was accomplished by testing all systems separately, then bringing them together in dummy runs without ignition or installing the motor. Once initial testing of the propane ignition system was completed, optimal propane flow was determined, at which point the ignition system worked as anticipated. The oxidizer flow is initiated, then after 2 seconds to allow the flow to stabilize, the propane flow is initiated. After one more second, the igniter is fired, igniting the propane and starting combustion in the hybrid motor. Propane is allowed to flow for approximately 0.5 seconds to ensure even grain combustion. After the preprogrammed firing duration, the oxidizer flow is shut off, extinguishing combustion in the chamber. The chamber is then purged with nitrogen to assure complete combustion termination.

A series of HTPB fuel grains were cast and then fired in the motor. A slight combustion instability, which is common with hybrid mo-

Table 1. Regression Rate Data for Hybrid Rocket Motor Using HTPB Fuel.

Grain Number	Run Number	Oxygen Flow (lbm/sec)	Oxidizer Mass Flux, G_o ($lbm/in^2 \cdot sec$)	Regression Rate, r (in/sec)
01	01	0.1620	0.2713	0.0407
01	02	0.1400	0.1551	0.0390
01	03	0.1200	0.1044	0.0286
01	04	0.1030	0.0736	0.0260
02	01	0.1760	0.2981	0.0390
02	02	0.0134	0.1426	0.0367
02	03	0.1190	0.0935	0.0230
02	04	0.1010	0.0656	0.0193
03	01	0.1720	0.2900	0.0397
03	02	0.1310	0.1409	0.0333
03	03	0.1160	0.0930	0.0240
03	04	0.1000	0.0655	0.0207
04	01	0.1120	0.1955	0.0347
04	02	0.0990	0.1143	0.0307
04	03	0.0783	0.0689	0.0203
04	04	0.0740	0.0538	0.0197
04	05	0.0578	0.0363	0.0137
04	06	0.0413	0.0236	0.0100
05	01	0.1240	0.2135	0.0360
05	02	0.1060	0.1190	0.0317
05	03	0.0910	0.0803	0.0228
05	04	0.0745	0.0561	0.0193
05	05	0.0575	0.0372	0.0150
05	06	0.0408	0.0237	0.0103
06	01	0.1150	0.1952	0.0387
06	02	0.0989	0.1084	0.0320
06	03	0.0826	0.0687	0.0210
06	04	0.0736	0.0513	0.0173
06	05	0.0585	0.0356	0.0143
06	06	0.0403	0.0222	0.0103

tors, was noted in the motor for both the Plexiglas and the HTPB fuels. With the HTPB fuel, the pressure oscillates less than 15% of the chamber pressure during a firing. Oxidizer flow and chamber pressure were increased until the maximum mass flow of 10 pounds per minute of oxygen and a chamber pressure of 500 psia were reached. A typical chamber pressure plot is shown in Figure 4. This completed the testing of the mechanical design of the motor and the check out of the entire facility.

The regression rate study was completed in February 1994. A total of 30 firings were completed. The fuel grains were weighed before and after firing to determine the mass of fuel used. This mass loss was then converted into a regression rate for the firing. The ablative substance applied to the ends of the fuel grains functioned appropriately, and no end grain burning was observed. The oxidizer mass flow was accurately measured for each firing, and the oxidizer mass flux was calculated. Over the

30 firings, the oxidizer mass flow was varied from 0.0403 to 0.176 pounds mass per second of oxygen. This range of oxygen mass flow, along with the average port diameter of the grain over the firing, gives an oxidizer mass flux that ranges from 0.022 to 0.298 lbm/sec·in.^{2} Regression rates from 0.0100 to 0.0407 inches per second were recorded. This data is show in Table 1 and Figure 5. Chamber pressures varied between firings from 180 to 400 psia, depending on oxidizer flow and motor nozzle size.

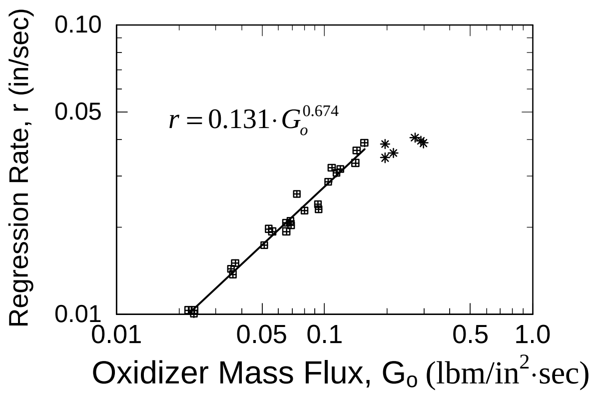

Figure 5. Plot of regression rate data for hybrid motor using HTBP fuel.

It can be noted from the data obtained that there exists a group of points that are distinctly separated from the rest of the data. These six points are for the initial firings for each fuel grain. It was hypothesized that because no opacifier was added to the fuel, the regression rate of those grains was lower. However, a char layer had been deposited on the fuel's surface at the end of these primary firings. This acted as an opacifier for the secondary firings, increasing the regression rate. This being the case, the data from the primary firings were separated from that of the secondary firings and each set used to determine the experimental results. A line was fit through the set of secondary firings. While the six points from the primary firings do not represent enough data to fit a valid line through them, they do seem to fall on the line as described in Sutton.[4]

For the data presented in Sutton, the constants a and n in the equation governing regression rate, were calculated to be a = 0.104 and n = 0.681. This gives the equation as follows:

$$r = 0.104 \cdot G_o^{0.681} \tag{2}$$

Since only six primary firings were completed, a more involved test matrix needs to be developed to test the theory that a char layer develops and increases regression rate.

For the data from the 24 secondary firings, the constants a and n, were calculated to be a = 0.131 and n = 0.674. When a and n are applied to equation 1, this gives

$$r = 0.131 \cdot G_o^{0.674} \tag{3}$$

This data has an error of $\pm$8.8%. This gives results that show a higher regression rate than shown in Sutton for HTPB fuel. It is speculated that if an opacifier is added to the HTPB grains, the primary firings would also show this increased regression rate. This was confirmed by preparing a fuel grain using carbon black as an opacifier. The regression rate of this grain on its primary firing was consistent (–3% error) with the secondary firings of the other grains. An oxidizer mass flux of 0.1562 lbm/(in^2·sec) gave a regression rate of 0.0363 in/sec.

Conclusions

A labscale hybrid rocket motor facility was developed, designed specifically as a testbed for the development of plume spectroscopy instrumentation (Figure 6). The computer control and data acquisition systems have worked effectively and efficiently to make this facility easy to operate. The choice of hybrid motor technology made it safe and cost effective as well. The regression rate study showed that the motor design and fuel give predictable results. This makes it feasible to dope the fuel grains with metal salts and calculate the concentration of metals in the plume. This capability indicates that the UALR hybrid based facility functions well as a testbed for the development of plume monitoring systems. The design of the facility, as implemented, has proven to be reliable and to give consistent results. Additionally, the ease of use and rapidity of set-up (up to 12 or more firings a day) make this facility an excellent

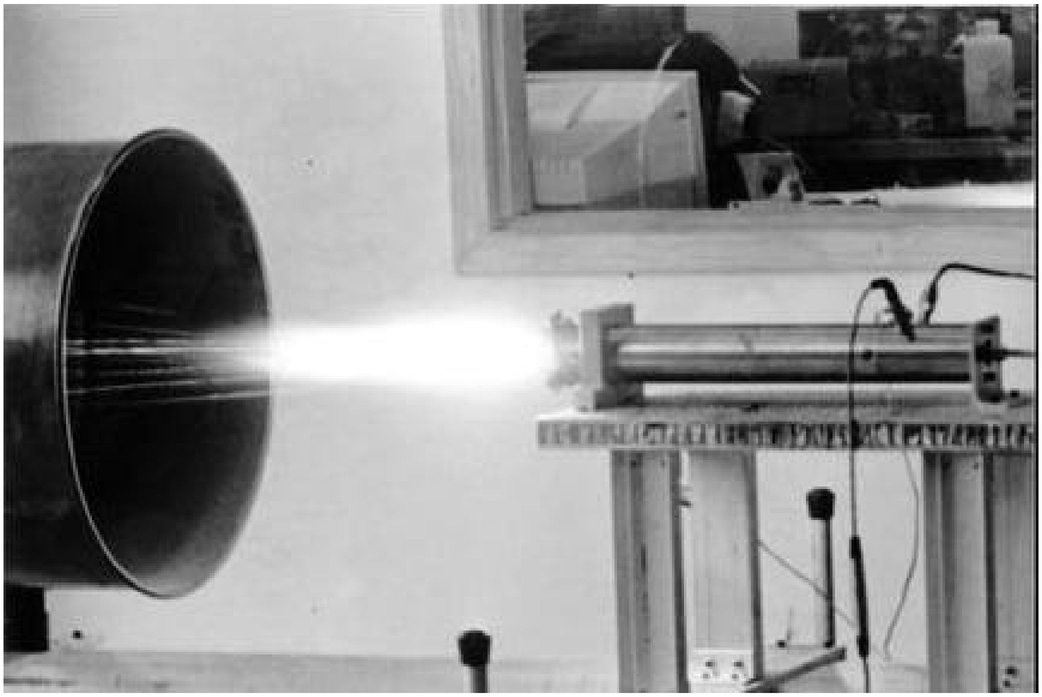

Figure 6. A typical HTPB firing of the UALR thruster.

testbed for all types of rocket motor studies, such as fuel composition, combustion stability, and base heating effects. Other oxidizers (nitrous oxide) could be studied, however, operating parameters would be necessarily quite different, since cylinder pressures would vary from that for gaseous oxygen.

Acknowledgments

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